Development of a Visuomotor Augmentative Sensory Aid for Visually Impaired Persons

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***Abstract*- Vision is the primary source of information about the surrounding environment. Human beings rely heavily on the sense of sight to carry out most of the activities necessary for survival. Visual impairment takes away the principal source of information about the immediate environment of an affected individual. Hence, visual impairment has been reported to limit independence and social inclusion, affecting the quality of life of affected persons. This work aims to develop a socially acceptable Sensory Substitution Device (SSD) known as a Visuomotor Augmentative Sensory Aid to aid blind and visually impaired people in navigating safely and independently. This is achieved using four HC-SR04 ultrasonic sensors that feed distance readings to an Arduino UNO development board. The Arduino performs filtering and processing on the sensor data before feeding it back to the user through customised vibrations. Evaluation of this work shows that the device is portable, user-friendly, lightweight, and socially acceptable, as indicated by the responses of the participants.**

***Index Terms*- Arduino UNO, Assistive Technologies, Blindness, Navigation, Visual Impairment.**

I. INTRODUCTION

Vision is a fundamental source of information from the surrounding world [1]. For humans, the sense of sight plays a pivotal role in physical health, interpersonal communication, independence, navigation, social interaction, academic and job opportunities, and socioeconomic status, all the way to how daily activities are carried out [2].

Visual impairment refers to any defect that reduces visual performance and cannot be cured using standard refractive correction lenses, medications, or other medically available methods. Blindness refers to the lack of the ability to detect any form of light [3], [4]. The Blind or Visually Impaired people (BVI) have been categorised into a spectrum because both groups possess limited eyesight even with visual enhancement aids.

For a very long time, visual impairment has been of concern all over the world. In 2010, the Global Data on Visual Impairment paper by the World Health Organization (WHO) reported 285 million people with visual impairment, out of which 246 million possessed low-level vision while the remaining 39 million were categorised as legally blind [5]–[7]. With the world population rapidly rising, 385 million people are estimated to be visually impaired, with 330 million possessing low-level vision and the remaining 55 million being legally blind by 2030 [8]. Many of the cases of those with visual impairments are a result of refractive errors, which could have been diagnosed and remedied but for the unavailability of the required medical resources [9]. The problem of visual impairment is said to be geographically predominant and can thus be attributed to many factors, the most notable being poverty-related conditions [9]. Notably, 90% of the visually impaired populace globally are from developing nations [9]–[11].

Visuomotor (coined from "vision" and "motion") skills refer to the skills required for coordination between the eyes and the feet or the eyes and the hands. Due to a lack or reduction in visual information, BVI individuals do not possess the luxury of independent navigation, especially in unknown or pedestrian-intensive environments [12]. This puts BVI in harm's way in the form of falls, road accidents, and many other ghastly scenarios with an increased associated risk in older adults [13]–[15]. The struggle is not limited to only independent navigation and mobility, it also cuts across emotional, social, and psychological well-being, ranging from the inability to participate socially to depression, social isolation, and many more daily cognitive challenges [4].

Various aids and sensor technologies have been developed to improve the quality of life of people living with visual impairment and blindness with respect to independent navigation [16]. Despite the proposed solutions to aid BVI people in navigating safely and independently, consideration is not given to the fact that 90% of the visually impaired populace globally is from developing nations. Hence, not many of those solutions are designed and implemented with BVI people in developing and under-developed countries in mind [9], [17], [18]. Also, not many of these devices address the issue of social inclusion faced by blind people in that these devices are conspicuous.

Therefore, this work aims to develop a visuomotor assistive aid for BVI persons. It is designed to remedy the difficulty in independent navigation and, also adopts cost-effective components to offer obstacle-avoidance functionality while preventing the user from experiencing social stigma. This research exhibits significant potential in furthering the achievement of United Nations Sustainable Development Goal 3, which pertains to advancing optimal health and well-being. The primary objective of this initiative is to effectively cater to the urgent requirements of a significant section of the global population who suffer from vision impairment.

Over the years, various studies and methodologies have been proposed to aid individuals with visual impairments in navigation and obstacle-detection tasks. The studies use diverse technological tools such as sensor-based systems, computer vision systems, ultrasonic sensors, infrared sensors, Internet of Things (IoT) technology, and artificial intelligence (deep learning algorithms) [19],

[20]. These technologies are harnessed to develop assistive devices such as laser range finders, Radio-Frequency IDentification (RFID) sensors with pre-installed RFID tags, a shopping robot for blind people – which guides the user in a store and informs them of the prices of commodities, white canes – a guide cane which is a robot combined with a white cane, Global Positioning System (GPS)-enabled devices like mobile apps on smartphones, etc. [21]–[23]. Depending on the technique adopted, those aids can be categorised as either Electronic Travel Aids (ETA), Electronic Orientation Aids (EOA), or Position Location Devices (PLD) [24]. Assistive devices have been meticulously engineered to optimise the efficacy of indoor and outdoor mobility, thereby furnishing a comprehensive framework for individuals afflicted with visual impairments, encompassing those who have complete blindness. The conducted studies utilise a range of feedback mechanisms, such as auditory commands, vibrations, and object identification, to provide directional information and enhance the detection of obstacles. Some of these works are presented hereafter.

An innovative electronic device called NavGuide, was designed to help individuals with visual impairments navigate obstacle-free paths. The device utilises advanced technology to provide real-time guidance and assistance, enhancing the mobility and independence of visually impaired individuals. Through sensory input and intelligent algorithms, NavGuide offers a reliable and efficient solution for path-finding. However, NavGuide's limitation is its inability to detect downhill slopes effectively. Additionally, the system can only detect damp floors after the user has already stepped on them [5].

A smart stick to enhance the mobility and safety of visually impaired individuals was developed. In order to provide auditory and tactile feedback to individuals with visual impairments, the buzzer and vibration motor are engaged upon detection of any obstructive object. However, the authors emphasised that this system may not be optimal for individuals with visual impairments due to its inherent complexity by providing caution instead of using vibrations or speech messages [6].

Another study conducted introduced a blind assistive system designed to aid individuals who are blind or visually impaired in identifying 80 frequently seen objects in their immediate environment. The system leverages the YOLO and Open CV libraries, renowned for their effectiveness in video processing tasks. The assistive system has undergone rigorous testing and has demonstrated excellent performance across various environments and conditions [25].

Smart directing devices have been developed to solve the problem of too extensive conventional guiding gadgets. The system can function as a comprehensive guide and is efficiently employed for traffic light identification, payment processing, and speech recognition tasks [26].

The smart cane developed here does not incorporate a water sensor. Nevertheless, the device does provide an extended standby time and is equipped with a rechargeable battery. The notifications generated upon detecting a barrier also include a tactile component. The device utilises a Raspberry-Pi 4B Camera, Ultrasonic Sensor and Arduino, mounted on the rod of individuals with visual impairments to function independently, even when internet connectivity is unavailable [7].

A low-cost visual aid was developed, and it provides obstacle detection, emergency contracting, surveillance and location, voice-controlled functions, and path navigation. The design caters for real-time analysis and functions simultaneously with the camera's recording procedure. Implementing an innovative lightweight jacket approach in the execution of the programme reduces the likelihood of unintentionally misplacing or losing traditional intelligent spectacles [27].

The work done by Ayesha Ashraf developed an Internet of Things (IoT)--powered smart stick designed to aid individuals with visual impairments. The device is equipped with an ultrasonic sensor and a buzzer to identify obstacles efficiently and emit an audible alarm. A mobile application was developed to facilitate the transmission of essential notifications and GPS coordinates to designated phone numbers. The authors also investigated the potential of image processing and interaction with the aid to enhance the user's comprehension of obstacle and object structures before receiving guidance from the aid [8].

II. MATERIALS AND METHODS

Instrumentation of the Visuomotor Augmentative Sensory Aid (VASA) for BVI

The core subsystems of the VASA are presented in Fig. 1. The sensing module is designed to be autonomous and hands-free, integrated into a user-wearable belt. It uses echolocation and HC-SR04 ultrasonic sensors to detect obstacles. The device uses a fusion of multiple ultrasonic sensors, mimicking bat swinging head motion and human echolocation, to provide better spatial comprehension and explore alternative routes for blind people. The Human Machine Interface uses vibration motor modules to avoid cognitive stress and electromagnetic waves, making it user-friendly. The modules are placed on both the left and right of the user, eliminating the need for continuous audio feedback. The Power Module consists of a switch and LNDIO PQ1019 power bank, which shares loads between the Arduino UNO microcontroller and DC vibration motor module, SG90 micro servo motors, and ultrasonic sensors. The switch conserves battery power, ensuring the device lasts for days before recharging.

Figure 1 The VASA Architecture

Design of the VASA

According to the design specification, the device is to be hands-free. This was achieved by integrating the device into a fanny bag the user can wear. The autonomy was accomplished by implementing echolocation into the device and processing the information feedback from that process. HC-SR04 ultrasonic sensors were employed to provide distance readings (through the principle of echolocation) to the Arduino to detect the distance to the nearest obstacle. However, the device cannot perform positional triangulation of the obstacle. Therefore, given that the blind person is alerted to the presence of the obstacle, the effort must be made in the form of lateral and vertical changes to avoid collision with the obstacle. The device then provides a solution to the need for blind people to explore and navigate by using a fusion of multiple ultrasonic sensors. This feature mimics the swinging head motion in bats and human echolocation experts. It is done to get a sample of the environment to obtain better spatial comprehension.

Figure 2 models the ultrasound signals being propagated from the HC-SR04 sensor. One of the design specifications is autonomy. This aims to offer adequate information for safe navigation with minimal thinking on the path of the user. This was achieved using three ultrasonic sensors (one in the centre and one sensor each on both the Left and the right side). The sensor at the centre faces the front (180o) while those to both the Left and the right are at an angle of 15o to the centre sensor. The Left and right sensors are also four centimetres (4cm) each from the centre sensor, as seen in Fig. 3.

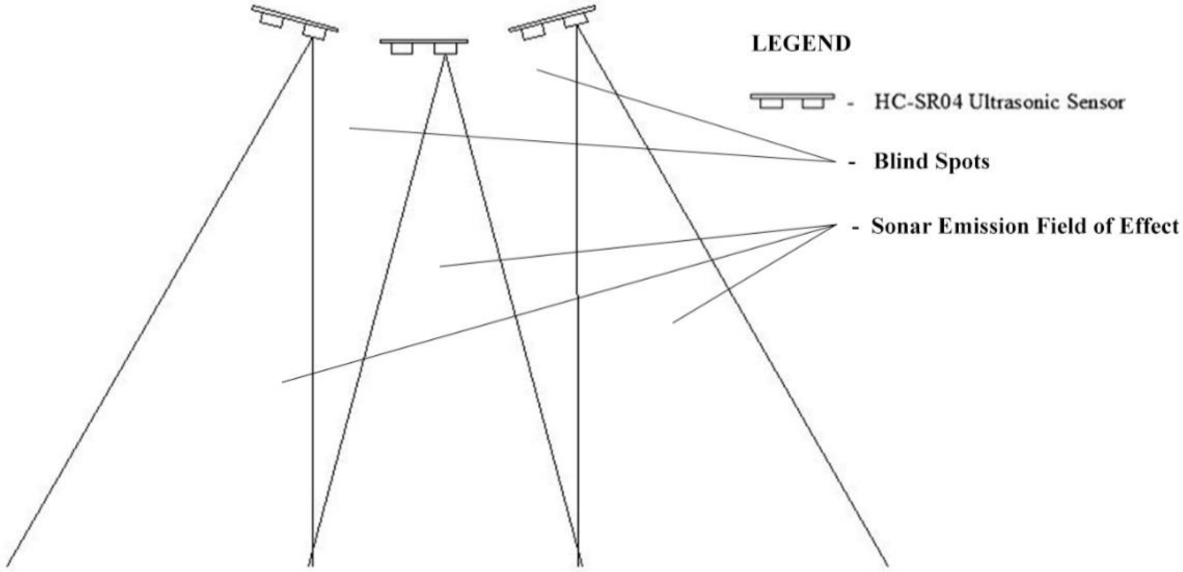

Figure 1 Diagrammatic Model of the Device and their Meanings

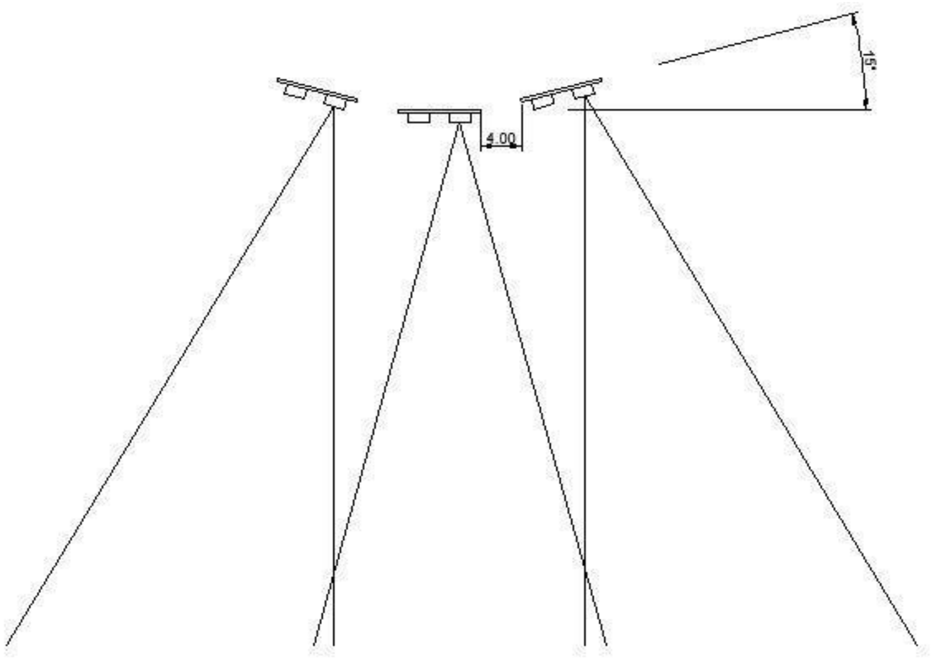

Figure 2 The Fusion of HC-SR04 to Achieve a Degree of Autonomy

The fifteen-degree (15^{o}) angle resulted from conducting several unit tests on the sensing module. These tests used angles like 10^{o}, 15^{o}, 22.5^{o}, 30^{o}, 45^{o,} and 60^{o}. The prevalent angle (15^{o}) remains the best option because it provides a sixty-degree (60^{o}) wide angle of coverage, as seen in Fig. 4.

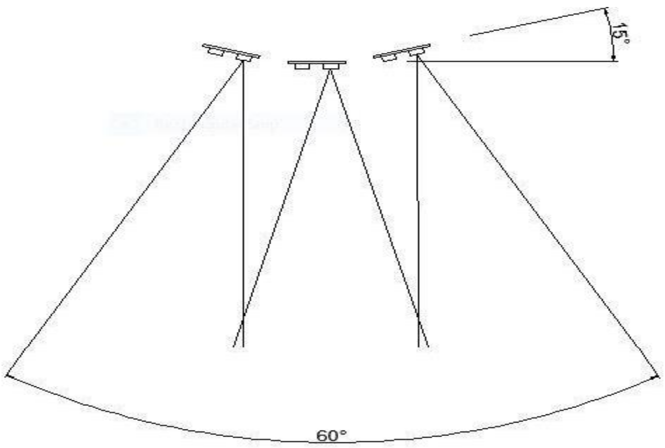

Figure 3 The Angle of Coverage Subtended by the Device

The sixty-degree angle was particularly important because the average shoulder width of an adult human person is about forty-one centimetres (41cm). At 50cm from the device, the device was able to protect an individual with maximum shoulder-width protection of up to 60cm. It also keeps the device's blind spots (the area(s) in which the three ultrasonic sensors cannot detect an object even though it is present) internal. Keeping the blind spots internal reduced the chances of collision due to undetected objects to the barest minimum for the sensor arrangement adopted.

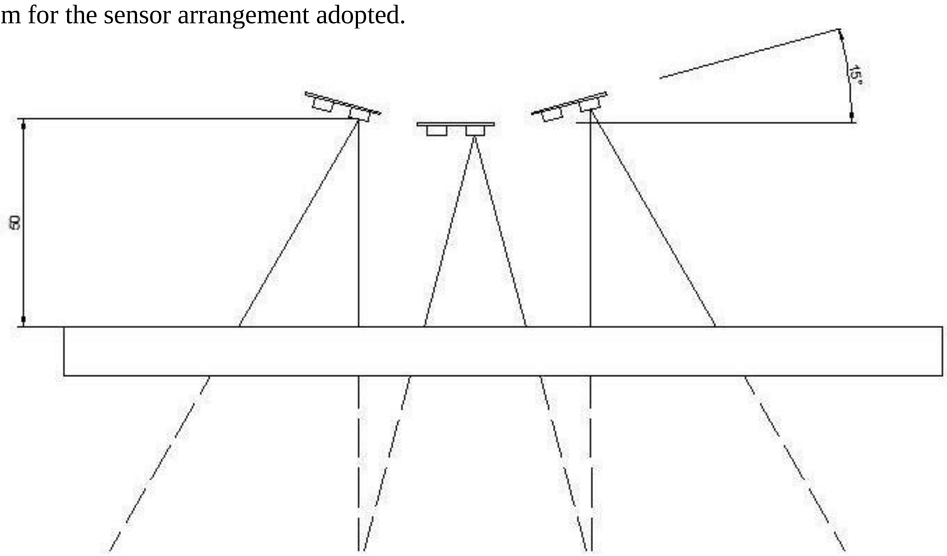

Figure 4 Image Showing all the Three Ultrasonic Sensors Blocked by an Obstacle

The fusion of sensors and the 15° angle difference functions properly except for situations where all three HC-SR04 sensors are blocked i.e. all three ultrasound sensors have values less than 50cm, with each sensor differing by a range between 5cm, as seen in Fig. 5. This scenario can play out when the blind person walks down a corridor and gets close to a wall at the end of the corridor. The device was designed with two micro servo motor SG90 on which the right and the left ultrasonic sensors for this purpose were mounted. When the above condition with the ultrasonic sensors is met, both servos move their respective ultrasonic sensors so that their new position is 90° to the centre ultrasonic sensor, as seen in Fig. 6. This was done so the sides (left and right) can be checked and a more straightforward path can be proposed to the user.

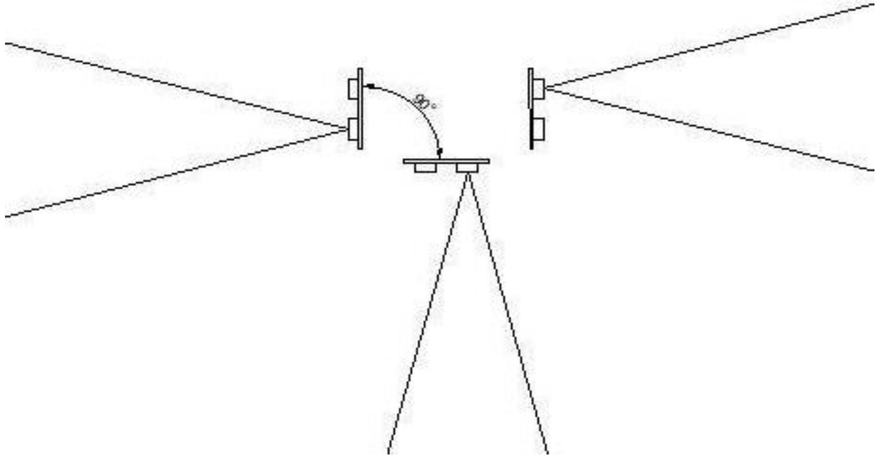

Figure 5 Image Showing the Ultrasonic Sensors Turned by the Servo Motor

The device can detect changes in the topography as the user moves around. This was achieved by imploring another HC-SR04 ultrasonic sensor. This ultrasonic sensor is facing the ground at an angle of 49^o. The angle of 49^o was chosen to prevent the device from reading the feet of the user as the topography changes. It accomplished this by considering the average stride length for humans, which is about 76.2cm or greater depending on the height of the individual. Figure 6 shows that the device reads changes at a distance offset of 93.75cm. This offered enough space for the user to take strides without affecting the device. The angle was obtained from simulation in AutoCAD, where the scenario was constructed, as seen in Fig. 7.

The 49^o angle chosen for the ultrasonic sensor facing the ground made this model more suitable for people above 5 feet tall. Figure 7 shows a vertical height of 91.44cm, which is converted to feet by dividing by 30.48 to obtain 3 feet. The 3 feet is the distance between the ground and the waist of the user where the bag is situated. It assumes that the user has a somewhat proportional body.

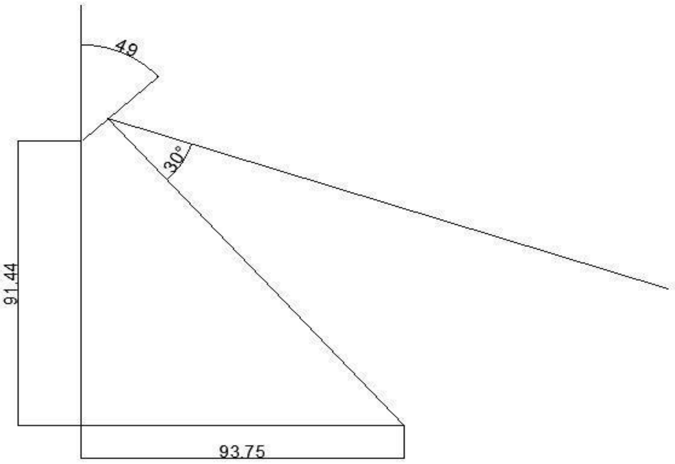

Figure 6 Representation of the Sensor Checking the Topography Change

Furthermore, the fusion of the ultrasonic sensors meets the design specification of adaptability. Unlike other assistive solutions for BVI people that require the location to be mapped before the device can function effectively or those that require interaction with global satellites, etc., this device can function adaptively in diverse environments with varying types and forms of obstacles.

Figure 7 The Visuomotor Augmentative Sensory Aid (VASA)

The vibration motor module characterised the Human Machine Interface. The device consists of three vibration motor modules, of which the Left and the Right straps of the bag have one module at the centre of the bag. The choice of vibration motor modules as the feedback mechanism came from the need to avoid putting the user under cognitive stress, which can be caused by continuous audio feedback. The vibration motor module also eliminates the presence of electromagnetic waves, which can affect users' health in the long run. It also met the design specification of free ears because nothing was placed close to/in the ear. The specification of the device being user-friendly was achieved as the device used a few simple vibration patterns. The feedback vibration patterns are given in Table 1.

Table 1 Vibration Patterns and their Meanings

Position of Vibration	**Meaning**
Right	Shift right
Left	Shift left
Centre (increasing intensity)	Going up
Centre (decreasing intensity)	Going down
Right and Left (simultaneously), then Right	Stop and turn right
Right and Left (simultaneously) then Left	Stop and turn left

Testing Protocol of the VASA

Demographics

This research utilised a hybrid methodology, employing both quantitative and qualitative techniques. The survey spanned five months, while in-depth individual interviews were conducted to gather qualitative data. The study involved a cohort of 100 individuals who were blindfolded to replicate the experience of visual impairment. These participants, aged between 18 and 29 years, possessed diverse educational backgrounds and came from various walks of life. Of the 100 participants in the test, ninety participants (90%) were in the age range of 18 – 20 years, four participants (4%) were in the age range of 21 – 25 years, and six participants (6%) were in the age range 26 – 29 years. The mean age of the study was 18.14 years The study was conducted in Covenant University, Ota, Ogun State, Nigeria.

Ethics

The study received approval from the Covenant University Health Research Ethical Committee (CUHREC) CHREC /177/2022. The researchers diligently sought the participants' consent before their recruitment for the study. The participants were duly apprised that their involvement in the study was voluntary, and they were further informed that they possessed the prerogative to withdraw from the study at any given time. Supplementary details about the study were duly disseminated to all eligible participants, and ample opportunities were extended to engage in inquiries prior to the commencement of the interviews.

Data Collection

The testing of the device was done in front of the Covenant University Shopping Mall, Covenant University Daniel Hall corridors and Peter Hall Common Room over a couple of days. The participants were blindfolded to simulate the instance of blindness.

The testing process occurred in two stages. In the first stage of the test, the individuals are blindfolded, and their ability to navigate a controlled environment with strategically placed obstacles is tested. During this stage, the number of collisions was recorded. The second stage involved the individual still being blindfolded, attempting to navigate the obstacle course while receiving instructions from the assistive device. Similar to the previous stage, the number of collisions made during this stage was also documented.

The questionnaire had five (5) questions regarding the design specifications: user-friendliness, independence during navigation, weight, portability, and autonomy, all having one question each. The questionnaire employed the 5-point Likert Scale with response options classified under Strongly Agree (SA), Agree (A), Neutral (UN), Disagree (D), and Strongly Disagree (SD). The levels of evaluation ranged from 1 (Strongly Disagree) to 5 (Strongly Agree). The data obtained from the questionnaire was analysed using IBM SPSS Statistics 20. The data analysis used central Tendency and dispersion indices for descriptive statistics. These served as the basis for assessing the developed device's validity and reliability. During the test, the number of collisions the participants made with the obstacles when blindfolded without the device and the number of collisions made when the device was in play were recorded.

III. RESULTS AND DISCUSSION

User Friendliness

This refers to the ability of the user to use the device and understand its functions efficiently. It also measures how easily the user can interact with the device. The 5-point Likert scale was used to evaluate the device on this specification, and the results are shown in Table 2. Two participants (2%) were neutral about the device being easy to use, thirty-two participants (32%) noted that the device was easy to use, sixty-six participants (66%) strongly agreed that the device was easy to use and understand. Altogether, no participant disagreed or strongly disagreed that the device was easy to use and understand.

Table 2 Relationship between Participant's Age Group and the Device' User-Friendliness

User-friendliness				
Participant's age group	**Neutral**	**Agree**	**Strongly agree**	**Total**
18 - 20	0	32	58	90
21 - 25	0	0	4	4
26 – 30	2	0	4	6
Total	**2**	**32**	**66**	**100**

Independence

This evaluates the ability of the user to depend entirely on the navigational cues offered by the device to navigate away from obstacles without the help of an external sighted individual. As shown in Table 3, two participants (2%) strongly disagreed that the device was sufficient for navigation. Another two participants (2%) disagreed that the device would function independently without the input of an external sighted observer. Six participants (6%) took a neutral stance on the device's ability to function independently. Thirty-six participants (36%) agreed that the device would function adequately without external help from a sighted observer. Fifty-four participants (54%) strongly agreed that the device was independent enough to act sufficiently as a navigation device.

Table 3 Relationship Between Participant's Age Group and the Device' Independence

Independence						
Participant's age group	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**	**Total**
18 - 20	2	2	6	32	48	90
21 - 25	0	0	0	2	2	4
26 – 30	0	0	0	2	4	6
Total	**2**	**2**	**6**	**36**	**54**	**100**

Lightweight

This evaluates the weight of the device when it is in use. As seen in Table 4, eight participants (8%) chose to remain neutral, twenty-eight participants (28%) agreed that the device was lightweight, and sixty-four participants (64%) strongly agreed that the device was lightweight.

Table 4 Relationship Between Participant's Age Group and the Device Being Lightweight

Lightweight				
Participant's age group	**Neutral**	**Agree**	**Strongly agree**	**Total**
18 - 20	6	28	56	90
21 - 25	0	0	4	4
26 – 30	2	0	4	6
Total	**8**	**28**	**64**	**100**

Portability

This is the evaluation of the device based on whether it was easy to carry around. As highlighted in Table 5, two participants (2%) disagreed and believed the device could be made smaller. Six participants (6%) remained neutral on the portability of the device. Thirty-two participants (32%) agreed that the device was portable and easy to carry. Sixty participants (60%) strongly agreed that the device was portable.

Table 5 Relationship Between Participant's Age Group and the Device Being Portable

Portability					
Participant's age group	**Disagree**	**Neutral**	**Agree**	**Strongly agree**	**Total**
18 - 20	2	4	30	54	90
21 - 25	0	2	2	0	4
26 – 30	0	0	0	6	6
Total	**2**	**6**	**32**	**60**	**100**

Autonomy

This is the evaluation of the device based on the amount of mental processing the user must do on the information coming from the device to navigate an environment safely. Two participants (2%) disagreed and believed they still needed to think and make their own decisions on where to move based on the information from the device. As depicted in Table 6, two participants (2%) remained neutral on whether they worked mentally on the device's information. Thirty-two participants (32%) agreed that the device did all the processing for them. Sixty-four participants (64%) strongly agreed that the device was autonomous enough.

Table 6 Relationship Between Participant's Age Group and the Device Being Autonomous

Autonomy					
Participant's age group	**Disagree**	**Neutral**	**Agree**	**Strongly agree**	**Total**
18 - 20	2	0	32	56	90
21 - 25	0	0	0	4	4
26 – 30	0	2	0	4	6
Total	**2**	**2**	**32**	**64**	**100**

From the above results with respect to functionality, the device reduced the number of collisions from three hundred and thirty-six (336) to ninety-one (91) in a controlled environment. Hence, only 27.1% of collisions in the first stage occurred in the second stage. This shows a significant reduction in the number of collisions by 72.92%.

Placing the HC-SR04 ultrasonic sensor facing the ground in the system at an angle of 49^o led to failures in acquiring accurate readings. This can be attributed to the laws of reflection in physics, particularly that the angle of incidence is equal to the angle of reflection. Hence, most of the sonar emitted toward the ground to obtain changes in topography was lost, leading to erroneous readings.

In the participant's subjective opinion of the device, 66% were convinced that it was easy to use and understand. Another 54% shared the same conviction in the device's ability to function alone and safely guide users around. 64% and 60% of the participants believe that the device was lightweight and portable to carry around with high confidence. 56% of the participants strongly agreed that the device carries out all the required processing and thoughts.

Although the study has an unevenly skewed participant age distribution, it was generally observed that the younger participants were keener and more critical about the sensory aid developed than the older participants. Their evaluations gave better insights on making the device more functional.

IV. CONCLUSION

The work done harnesses the principles of echolocation to determine an individual's distance from an object to provide information necessary to evade the object. The developed device is functionally efficient, portable, user-friendly, light, and socially acceptable, as evident in the results based on the subject opinions of the test participants.

However, the testing process of this device exposed the following limitations: cost as a constraint acts as a significant barrier to the development of devices with robust functionalities and optimal accuracy. The device lacked the ability to sense dynamic objects at a moderate or high speed; it was unable to detect overhanging obstacles; it had to continually compute data from the environment due to its inability to learn, and the device did not provide a navigational prompt to its users.

Hence, it is recommended that smaller, low-cost processors with sufficient computing power can be developed. Cheaper sensors with higher accuracy and multiplexed functionalities can be developed. Further works can integrate sensors to observe the overhead environment for obstacles. Learning algorithms can also be implemented to reduce computational power and increase computational speed and device accuracy. GPS functionality can be added to the device both for localisation and orientation and for the user's navigational direction. Image sensors and image processing algorithms with necessary sensors can be used to capture, analyse and localise obstacles in motion to help the user evade them.

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